The scientific basis for human bitemark analyses – a critical review

IA PRETTY*

Faculty of Medicine, Department of Clinical Dental Sciences, Daulby Street, The University of Liverpool, Liverpool, L69 3GN, United Kingdom

and

D SWEET

Director, Bureau of Legal Dentistry, Vancouver, British Columbia, Canada V6T 1Z4

Science & Justice 2001; 41: 85–92

Received 27 November 2000; accepted February 2001

This article presents a discussion of the scientific basis for human bitemark analyses. Using a review of the literature, the major areas of contention within the field are assessed: including the accuracy of bitemarks on skin, the uniqueness of the human dentition, and analytical techniques. The review revealed a lack of valid evidence to support many of the assumptions made by forensic dentists during bitemark comparisons. The new level of judicial scrutiny of such scientific evidence is likely to emphasise this lack of knowledge upon which bitemark analysis relies. The authors call for a more scientific and evidence-based approach to forensic dental research.

In der vorliegenden Arbeit diskutieren die Autoren die wissenschaftliche Basis zur Analyse von humanen Bissspuren. Anhand eines Literaturüberblicks wurden die in diesem Wissensgebiet existierenden Hauptstreitpunkte bewertet. Dies schließt ein: Die Genauigkeit von Bissmarken auf der Haut, die Einzigartigkeit des menschlichen Gebisses sowie analytische Techniken. Der Überblick enthüllte einen Mangel an stichhaltigen Beweisen für viele der Annahmen, die von forensischen Zahnärzten bei dem Vergleich von Bissmarken gemacht werden. Auch die neuerliche kritische Wertung solcher wissenschaftlicher Beweise durch Gerichte wird wahrscheinlich diesen Mangel an Wissen hervorheben, auf dem die Analyse von Bissmarken fußt. Die Autoren rufen die forensische Dentalforschung zu einer wissenschaftlicheren, beweiskräftigeren Vorgehensweise auf.

Cet article présente une discussion des bases scientifiques concernant les analyses de morsures humaines. En utilisant une revue de la littérature, les domaines de discussion principaux dans le domaine ont été déterminés, y compris l'exactitude des marques de morsures sur la peau, l'unicité de la dentition humaine et les techniques analytiques. Cette revue montre un manque de données valables pour soutenir plusieurs assomptions faites par les odonto-stomatologues dans le cadre de la comparaison de morsures. L'augmentation du questionnement judiciaire sur de tels moyens de preuve scientifique va certainement mettre en exergue ce manque de connaissances sur lesquelles l'analyse de morsures se fonde. Les auteurs souhaitent une approche plus scientifique et basée sur les preuves pour la recherche dentaire forensique.

Este artículo presenta una discusión sobre las bases científicas de los análisis de mordeduras humanas. Se valoran las principales áreas de controversia de este tema utilizando una revisión de la literatura: esta valoración incluye la exactitud de los mordeduras en la piel, la unicidad de la dentición humana y las técnicas analíticas. La revisión reveló la falta de evidencia válida para sostener muchas de las asunciones hechas por los dentistas forenses durante las comparaciones de mordeduras. El nuevo nivel de escrutinio judicial de dicha evidencia científica parece enfatizar esta falta de conocimientos en los que se apoyan los análisis de mordeduras. Los autores convocan a un enfoque más científico y basado en la evidencia para la investigación forense dental.

*Corresponding author

Key Words: Forensic science, odontology, forensic dentistry, bitemarks, review, validity, uniqueness.

Introduction

Bitemarks are featured in some of the most violent and heinous crimes [1]. Their use to prove violent contact between suspect and victim has played an important role in many investigations and they have often represented the only physical evidence in such cases. Despite the continued acceptance of bitemark evidence in European, Oceanic and North American Courts the fundamental scientific basis for bitemark analysis has never been established. This review analysed the peer-reviewed research available to support bitemark evidence in light of the increased judicial scrutiny of forensic sciences.

It is useful to point out that the vast majority of forensic dental literature relates to the use of dentistry in determining the identity of found human remains, so-called 'dental identifications'. The effectiveness of dental identifications is well established and rarely questioned in Court. The unique features of the human dentition used in personal identification cases are legally and scientifically well accepted [2]. These features should not be confused with the individual characteristics of teeth used in bitemark identification cases. The debate over this issue is discussed in depth later in this review. The practice of bitemark analysis is highly contentious and yet the issues associated with the technique do not appear to have initiated a desire among the community to deal with these topics in the literature. The relative lack of material may reflect the inherent difficulties in bitemark research or time available to general dental practitioners for research.

Analysis of the articles

MedLine was utilised to locate articles pertaining to the forensic use of bitemark evidence. Searches were performed on the entire database, 1960–1999. In total 1508 articles were found that contained the keyword 'Forensic Dentistry'; 120 English language papers within this group were related to bitemarks. Each of these papers was located and, using ISI Web of Science, a Science Citation Index value was determined. For comparison purposes, it should be noted that within the 1960–1999 MedLine database there are 1457 articles related to Forensic DNA, 60 related to Forensic Entomology, and 3538 related to Periodontology.

Due to the relatively small number of papers found, it was possible to identify trends within the entire search. Approximately 20 papers have been published on the subject each year and the mid-eighties were the most productive period. The type of publication is an important aspect to consider when evaluating the core research and scientific basis for bitemarks. Figure 1 shows the distribution of the categories of papers among those identified in this research. It is interesting to note that case reports were responsible for 28% of the total literature while empirical research from well-designed experimentation contributed only 15%.

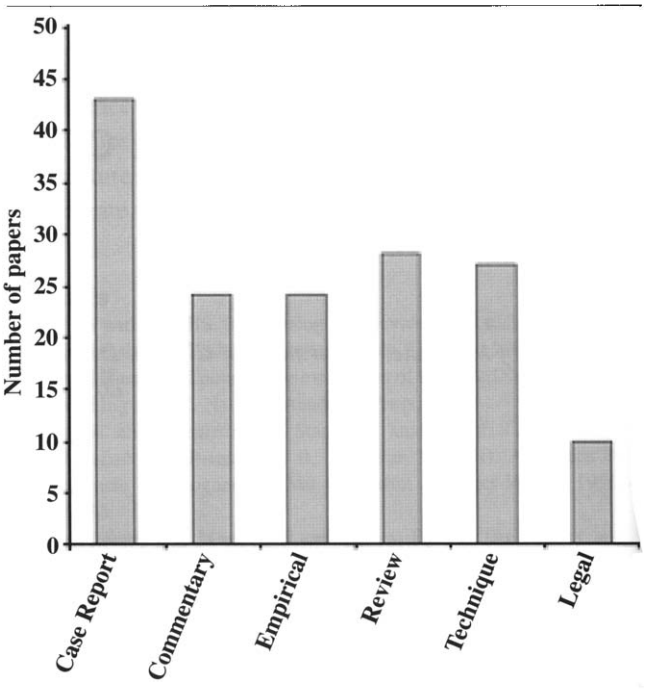

FIGURE 1 Common categories of publications in the bitemark literature, from 1960–1999.

Forensic dentists, lawyers, and others involved in the criminal justice system are concerned by this lack of a sound scientific basis for bitemarks. The lack of empirical evidence for a variety of assumptions made by forensic odontologists is frequently alluded to in the Courts, especially in the US. However, the forensic dental community continues to rely upon those few articles that have addressed the scientific issues. The plethora of case reports, reviews and anecdotal commentaries cannot address this deficit.

Many techniques have been developed to assess the value or quality of scientific articles. One such measure is the citation value. The citation value indicates the number of times that a particular article has been cited in another paper. The argument is that other authors will cite well-respected and valid papers, thus, the quality of the paper can be quantified.

Citation analysis has many critics who state that the judgement of papers based upon a single value is flawed. A simple variable, such as the number of researchers in a particular field, will have a significant impact on the citation value. Others state that reviews, which are often considered of poorer scientific value than empirical research, are frequently cited. This argument also extends to papers that describe laboratory techniques that are subsequently used by researchers in their own work.

Use of the citation value in this article is judged valid, as the subject papers are from the same discipline. The citation value has been used to assess those papers that are regarded as significant within the field. Any reader of the forensic dental literature will be able to identify three or four articles

that are constantly quoted. However, just how valid are these works?

For those papers that have been cited since publication, the mean citation value was 8.1, although only 53 of the 120 papers examined had been cited at all. It is also important to recognise that self-citation can also contribute to the citation value. The frequency of reviews on the subject of bitemark analysis is also responsible for many of the citations. Rothwell's 1995 review breathed life into many papers that had never been cited, or had not been cited for several years [3]. The popularity of forensic reviews in the general dental literature guarantees that such papers will continue to be cited giving an impression of continued scientific growth that belies the actual publication practices of the discipline.

Rather than summarise the entire body of the literature, those papers that address the main areas of contention within bitemark analysis will be presented. Contentious areas in bitemark evidence are well accepted as the: a) accuracy of the bitemark itself, b) uniqueness of the human dentition, and c) analytical techniques [3]. Each of these is discussed below.

Accuracy of bitemarks on human skin

The use of dental impression materials to record the features of the teeth and surrounding hard and soft tissues is well known and accepted [4]. Such materials are used in general and specialist dental practice daily to produce study casts and prostheses. A large volume of biomaterials literature and the anecdotal evidence of treatment success have established the accuracy of such materials. The considerable variation of bitemark presentations on human skin brings the accuracy of skin as a registration material into doubt [3]. While many studies have examined the accuracy of bitemarks on other substrates, such as cheese [5,6], apples [7], sandwiches [8,9], and soap [10], this review is restricted to human skin. This represents both the most debated area of substrate accuracy and the most commonly bitten material [11].

Skin is a poor registration material [12] since it is highly variable in terms of anatomical location, underlying musculature or fat, curvature, and looseness or adherence to underlying tissues [13]. Skin is highly visco-elastic, which allows stretching to occur during either the biting process or when evidence is collected. In 1971, DeVore issued a preliminary report describing studies performed on the variability of bitemarks found on skin [14]. The experiment involved the inking of human skin (living volunteers) using a stamp with two concentrically placed circles with intersecting lines. The resultant mark on the skin resembled a target. Following the placement of the stamp, the inked area was photographed with a scale in place. The subject was then instructed to change positions, e.g., from lying to sitting or to move an extremity from extended to flexed. The geometric pattern of the stamp was then re-photographed and the resultant prints compared to assess the degree of distortion.

Following analysis of the photographs it was found that in all cases there was an expansion or shrinkage of the stamp, with a maximum linear expansion of 60% at one location [14]. The design of the stamp permitted the investigators to examine the distortion in both size and direction. DeVore concluded that, due to the level of distortion found, photographic images of a bitemark in comparative analysis should be used only if the exact position of the body can be replicated. The placement of a body in such a position is usually impossible, as the exact position of the body during an attack is rarely known. DeVore stated that further research to investigate the effect of postmortem changes on skin distortion were required.

In 1974, researchers from the Bioengineering Unit of the University of Strathclyde examined the features of the biting process likely to impact upon the appearance of bitemarks on human skin [15]. They described the differing characteristics of skin from a variety of anatomical locations; e.g., Langer's Lines represent directional differences in the degree of extensibility of skin. Like DeVore, they emphasised the importance of body location during biting as the directional variations or tension lines will alter with movement. The report also described distortion that can occur in skin after biting. The oedematous response of skin to trauma is likely to stiffen the area, thus rendering it more stable. However, the subsequent resorption of this fluid will cause a large amount of distortion. They concluded that the changes in bitemark appearance are likely to be greater as the injury grows older. This was found equally applicable to both living and dead victims. The article concluded that forensic odontologists were "still ignorant...of the conditions during normal biting...considerable research is required [to address this]".

It was not until 1984 that this unresolved issue was re-visited with an examination of the morphology of breast tissue. Rawson and Brooks published a paper in which they classified breast morphology to assist with the determination of distortion of bitemarks in this location [16]. It is interesting to note that Rawson states:

> "The nature of skin and its underlying structures are still of some concern and will probably be a major source of research interest during the next decade."

The paper reviewed the literature regarding breast morphology but did little to explain how this could affect bitemark analysis. Following this paper, no other articles considered the topic from a physiological or anatomical viewpoint. Instead, attention was turned to the photographic treatment of distortion, and 1984 saw the publication of Krauss'

article on photographic techniques [17]. Subsequent articles were published, including those on the development and use of appropriate photographic scales, yet no further work was performed on the quantification of bitemark distortion on human skin [18]. The discipline seemed more interested in dealing with the distortion during evidence collection rather than considering the nature and degree of distortion that may have occurred at the time the injury was produced. Rawson's expectation for further research has not been realised.

There are probably several reasons why the issue of skin distortion has not been addressed further. Such research is expensive, involves human subjects and ethical reviews, and may require skills not normally held by forensic dentists. These difficulties are compounded by the difficulty of obtaining research funding from traditional sources (MRC, NSERC, NIH, etc.) for forensic research. From this review of the literature, it is possible to state that the issue of skin distortion in bitemark analysis has not been fully addressed and the cautions issued by DeVore and others should still be heeded today.

The uniqueness of the human dentition

Bitemark analysis is based on two postulates: a) the dental characteristics of anterior teeth involved in biting are unique amongst individuals, and b) this asserted uniqueness is transferred and recorded in the injury [19]. A distinction must be drawn from the ability of a forensic dentist to identify an individual from their dentition by using radiographs and dental records and the science of bitemark analysis. Dental identification, as opposed to bitemark identification, utilises the number, shape, type, and placement of dental restorations, root canal therapies, unusual pathoses, root morphology, trabecular bone pattern, and sinus morphology [2].

The debate over the uniqueness of human teeth is probably one of the fiercest in current forensic dental discourse. Many forensic dentists, appellants, and lawyers have questioned the validity of dental uniqueness determination and demand to know from testifying experts the relative frequency of dental features identified in bitemarks. An examination of the literature divulges the scientific evidence for this commonly held belief.

The first article to consider the statistical nature of dental uniqueness was published by MacFarlane and Sutherland in 1974 [20]. The authors began by differentiating between "positive" and "negative" features of the dentition. A positive feature was described as the presence of a tooth with a certain rotation or other individualising feature. A negative feature was the absence of a tooth. This study concentrated on the positive features that occurred on the anterior teeth (canine to canine, maxillary and mandibular). Patients were selected from an outpatient clinic and in total 200 study casts (maxillary and mandibular) were produced. The authors only studied the dental casts, not bitemarks that would have been produced by such casts.

The investigators noted the number and shape of each tooth, the presence of any incisal restoration, relationship of teeth to arch form, and tooth rotation (four categories). The study did not examine the presence or absence of spacing between teeth. The assessments of each cast were entirely subjective. Disappointingly, the authors elected not to publish a table of results. Rather they presented images of typical casts and calculated, using their data, the frequency of the traits shown. The authors noted that certain characteristics were not inter-related and thus the products of their incidences could be used to indicate an overall frequency. However, certain features, such as mesio-palatal rotation of the upper central incisors were inter-related with a significance of $p<0.001$. The authors stated that mesio-palatal rotation of the maxillary central incisors should therefore be taken as a single feature. This demonstrated that the true frequency of such features was almost four times greater than the frequency when the rotations were considered as individual variables.

In an example, MacFarlane *et al* concluded that a particular dentition would only be seen in eight people in 100,000 of the population with natural teeth. This figure was introduced in a US trial to much debate [21]. The authors concluded that they had not confirmed the individuality of the human anterior teeth, nor had they considered the impact or representation of any of the features examined on a bitemark in human skin. The highly subjective examination of the casts by multiple examiners and lack of tabulated results make this study weak, especially in light of the increased scientific scrutiny required by recent Court rulings. However, a large sample (200) was used of a defined population and efforts were made to ensure that this sampling was randomised.

The next paper to address the issue of individuality of human teeth was published in 1982. Authors frequently cite it as conclusive evidence for dental individuality [22]. The premise of the paper was to examine the dentitions of five pairs of monozygotic (identical) twins and, should individualisation among the pairs be established, to extrapolate this finding to the general population. The twins were selected from another, unrelated study and the authors state that no selection based on dentition was performed. None of the subjects had crowns or removable prostheses. All teeth were determined to be healthy and representative of young adults in their early 20s. Each twin underwent a complete oral examination including alginate impressions.

The impressions were immediately cast in plaster and subsequently epoxy-resin replicas of the anterior teeth were made and used to create test bites in a variety of materials,

including plaster of Paris and silicone impression materials. The test bites were then treated by the wax radiographic technique for overlay production and the resultant radiographs were analysed by computer.

A large number of measurements were carried out by the investigators who carefully noted asymmetries in each of the anterior teeth, angulations of test bites, and the depth of the test bites. Although the article stated that efforts were taken to standardise the production of these test bites, there was no discussion of how this was obtained. One crucial aspect would have been the amount of pressure applied to the epoxy replicas when creating the test bite. Many of the individual features claimed by the authors were dependent on the depth of penetration of the test bite into the substrate, and therefore a standardisation of this pressure would have been necessary. The substrate, plaster of Paris, has very dissimilar properties to that of human skin.

It should be noted that many of the differences between the

FIGURE 2 Variation in bitemark pattern that can be obtained by using the same dentition applied to dental wax using increasing pressure.

bitemarks described by the authors could be explained by the depth of substrate penetration (and hence increased width of tooth outline) by the replicas. The authors noted that the teeth did not meet at the same horizontal plane at the incisal edges in each twin. This is described as an individualising difference between the twins rather than as an artefact of experimental variation. Figure 2 shows the difference in test bite outline produced from the same dentition applied to wax at a variety of different pressures.

Even if it was to be accepted that the variation caused by inconsistent pressure application is negligible, the selection of substrate is questionable. Are investigators interested in the representation of uniqueness in plaster of Paris or human skin? Should a study that determined morphological human dental uniqueness in wax or plaster be extrapolated to fulfil a legally sound statement that a bitemark on skin is unique? With the current interest in the proper application of the scientific method, this would be unlikely to meet the legal burden. Sognnaes concluded that, in terms of dental arch form and individual tooth position, even identical twins are not dentally identical [22]. As previously mentioned the effect of different wear-and-tear rates, exposure to environmental factors, dental treatments, and disease experience among such individuals will obviously cause differences over time.

The twin study, despite the described problems, is one of two papers frequently cited as resounding evidence for the uniqueness of the human dentition. The other is Rawson's 1984 article 'Statistical Evidence for the Individuality of the Human Dentition' [23].

Rawson, an author on the twin study, in co-authorship with another dentist, two dental students and a statistician, wrote arguably the most cited and well-known bitemark paper describing an empirical experiment. In an attempt to prove finally the uniqueness of the anterior segment of human teeth, Rawson examined 397 bites and applied a statistical probability theory to the results. The significance of this paper warrants the comprehensive assessment of its validity that follows.

Twelve hundred wax bites were obtained from forensic odontologists in various geographic locations in the United States. Each bite was made on a custom wax wafer 1 mm thick supported by a 1 mm hard cardboard backer. The subjects were instructed to bite to the maximum depth of 1 mm. This design removed the variation of incisal penetration found in the twin study. A calibrated 1 cm scale was also impressed upon the wax.

From the 1200 samples received, 384 bites were selected although this was later increased to 397. It is unclear as to how this selection was made. There is no indication that this was a randomised sample. In order to adhere to strict scientific methods, the bites should have been selected in a random fashion to prevent any selector or observer bias being introduced. Rawson stated that the screening process involved an assessment of the clarity and accuracy of the marks as well as the completeness of an accompanying questionnaire. Another aspect of the study that is unclear is at what point the sampling was performed. Was it before or after the radiographic treatment of the bites?

The bitemark indentations were filled with zinc powder and then radiographed using a technique designed to minimise any enlargement. Following the exposure of one side of the wax the zinc was removed and the procedure repeated for the other side. A study determined that the radiographic process for overlay production was relatively accurate but it found that hand-traced overlays were less accurate and generally unsuitable for use [24]. Rawson's study used a combination of both techniques thus increasing the chance of errors considerably. In this study, the radiographic overlays were enlarged three times and then hand-traced on to gridded computer paper. The article stated that the resolution of bitemark examinations should be within 1 mm of the centre point of a tooth and 5 degrees of rotation. Results of the Sweet study suggested that this resolution might be difficult

to obtain using the hand tracing method [24].

Following the selection of the bites, the population sample was described as shown in Table 1. A comparison of these figures to US census data found that the population sampled in the study was a reasonable measure of the US population, although African Americans were under-represented and Orientals slightly over-represented.

Following the tracing of the biting edges, several elements of tooth position were assessed. A center point for each tooth was determined and the x and y co-ordinates noted. The angulation of each of the teeth was measured and all the data were entered into a computer for analysis. It was determined that the minimum number of positions that a tooth can occupy is 150 and the greatest 239.9. These figures were determined by multiplying the number of positions of x by y and by the angles observed. The occurrence of fractions of positions (i.e. 239.9) is a reflection of this multiplication. Rawson elected to use 150 as the number of possible positions for each tooth as this represented a conservative sample. Using this premise, the article then stated that the probability of finding two sets of dentition with all six teeth in the same position was 1.4×10^{13}. With an assumed world population of four billion (4×10^9) Rawson stated that a match at five teeth on a bitemark would be sufficient evidence to positively identify an individual as the biter to the exclusion of all others.

One concern with this use of the product rule to multiply individual probabilities to establish an overall likelihood is that of independence of the variables. The article assumed that the position of each of the teeth was entirely independent of the position of any others. However, the independence of these features has not been established by this or any other study. This has been shown incorrect; e.g., the dependence of mesio-palatal rotation described by MacFarlane [20]. It is likely that every tooth position influences another intra-quadrant, intra-arch and between opposing arches. This lack of independence renders Rawson's certainties of individualisation invalid. Rawson's results also showed a possible sampling error, as evidenced by the data sets regarding possible tooth position for each unit. Intuitively it should be anticipated that the left and right quadrants should represent a mirror image of each other in terms of possible tooth centre positions. This was not the case. The upper right lateral incisor was reported to have 239.9 possible locations while the upper left lateral incisor had 161.5 locations.

It can be argued that this paper, without the statistical treatment, confirms the anecdotal evidence of almost any practising dentist that the human dentition is unique. It can be stated that, with an extremely high resolution of measurement, such as in this article, the minutia of the dentition can be described and proven unique. The current authors would argue that this is the wrong question to ask. It is the rendition of these asserted unique features on human skin that is the unknown quantity. Rawson alluded to this point within his article:

> "... [the question is] whether there is a representation of that uniqueness in the mark found on the skin or other inanimate objects".

Rawson has proven what his article claims, although perhaps not to the mathematical or statistical certainty expressed. The article determined that the dentition is unique, however, when this paper is cited, authors often extend this conclusion to incorporate the uniqueness of bitemarks. The question of bitemark uniqueness remains unanswered.

The current authors believe that the problem can be approached more successfully from another perspective, that of bitemark analysis. By examining the ability of forensic dentists to identify correctly biters from their bitemarks, the issues of bitemark uniqueness can be answered. If it is apparent that odontologists have a great deal of difficulty in correctly identifying bitemarks, the question of uniqueness will become moot.

TABLE 1 Distribution of males, females, and races in Rawson's study.

Ethnicity	*Number*	*Percent*
Male	222	55.9
Female	175	44.1
White	301	75.8
Black	28	7.1
Oriental	33	8.3
Hispanic	24	6.1
Other	11	2.7

Analytical techniques

An essential component of the determination of the validity of bitemark analysis is that the techniques used in the physical comparison between suspect dentition and physical injury have been assessed and found valid. One of the fundamental problems with this task is the wide variety of techniques that have been described in the literature. Techniques using confocal, reflex and scanning electron microscopes, complex computer systems, typing of oral bacteria, special light sources, fingerprint dusting powder and overlays have all been reported [25–29]. It is a widely held belief that while methods that are more esoteric exist, the dominant technique for comparison of exemplars is transparent overlays.

The lack of direction from the forensic dental organisations,

TABLE 2 Various overlay fabrication techniques ranked according to accuracy. After Sweet and Bowers [24].

Rank	*Area*	*Rotation*
1	Computer-based	Computer-based
2	Radiopaque wax	Xerographic
3	Hand-traced from wax	Hand-traced from wax
4	Hand-traced from study casts	Hand-traced from study casts
5	Xerographic	Radiopaque wax

both European and American, complicates this matter. The American Board of Forensic Odontology (ABFO) has reported advice and guidance on many aspects of bitemarks and yet one of the most pivotal questions, i.e. what is the best comparison technique to use, has not been addressed [30,31]. Should a Court wish to review the literature to ensure that a testifying expert is using generally accepted techniques they would find the task daunting and ultimately unrevealing.

It is difficult for many dentists to gain access to a microbiological laboratory or SEM in order to employ some of the suggested comparison techniques. Indeed, many of the minority techniques are reported once in the literature and are never cited or utilised again. Such techniques are often criticised by the practising odontologists as nothing more than the products of ivory tower thinking. Transparent overlays utilise materials found in any dental office. The vast majority of forensic dentists use techniques that utilise materials that are inexpensive and easily obtainable, hence the popularity of overlays.

There are numerous techniques for the fabrication of transparent overlays. The only article that has assessed the accuracy of such overlays is that of Sweet and Bowers in 1998 [24]. This paper compared five common techniques of producing transparent overlays. Of all the techniques, an examination of case reports and experiments reveals that the xerographic and radiographic techniques are the most popular.

Sweet and Bowers used thirty randomly selected study casts to examine the accuracy of overlays produced from each of the five techniques concerning tooth rotation and surface area. The computer-generated overlays were the gold standard. See Table 2. From these results, it can be seen that the computer technique represents the most accurate fabrication method with respect to representation of rotation and area of the biting edge. The authors of the paper concluded that the fabrication methods that utilised the subjective process of hand tracing should not be used in favour of techniques that are more objective. The use of computer-generated techniques was advised over any other method.

The study described is an example of an experiment quantifying the techniques that are used in bitemark analysis in order to ensure that the most effective systems are employed. While the paper determined the accuracy of the overlays, it did not address the application of these overlays to the successful identification of a biter. Sweet and Bowers recommended methods in bitemark analysis that are more objective. Unfortunately, even if an objective technique is used, the subsequent comparison of this to a photographic reproduction of a bitemark is largely a subjective process.

Attempts have been made to carry out the entire analysis within a computer system. One of the most recent articles describing this work used a specially designed computer and software to perform complex image analyses requiring no interaction with the operator [32]. The entire system was objective and required the odontologist to merely scan the suspect's dentition and the bite injury into the computer. The use of representative correlation co-efficients was proposed to identify the most likely biter. Despite the promising nature of the project, when it was applied to a real bitemark case the incorrect biter (based upon a Court decision) was implicated by the system. In his discussion of these results, Naru states that the skin may simply not record the dentition accurately enough to enable analysis. The pathological record of the bite on skin is subject to many variables, such as distortion and colour changes that confound computer systems [32]. Naru recommended that further work would be required to modify the algorithms to contend with these variations.

Currently, the best practice for physical bitemark comparisons should be regarded as a life-sized computer-generated overlay that is carefully compared with a scaled 1:1 photograph of the injury. The use of multiple photographic images and the careful collection of the evidence from both victim and suspect should control distortion. The need for a completely objective bitemark analysis system is recognised, although the problems of variability of presentation of the injuries may render this ideal difficult to accomplish.

Summary

In her excellent legal review, Zarkowski states that bitemark analysis has never progressed through the rigorous scientific examination that is common to other sciences to determine its accuracy or reliability [33]. This review has highlighted the lack of hard scientific evidence to support the assumptions made by forensic dentists when analyzing bitemarks. Major areas of contention have been discussed but there is still no consensus of opinion or definitive research concerning these, especially in relation to the dental/bitemark uniqueness issue. Nonetheless, the use of computer-generated overlays in conjunction with techniques to control distortion is the most objective physical comparison

process available at present. It is important to mention that research in bitemark identification using salivary DNA has progressed over recent years [34,35]. This highly objective method of analysis is to be recommended but, due to DNA degradation, cross-contamination or insufficient DNA quantity, it cannot be used in every case. For these reasons, physical comparisons of bite injuries are likely to play an important role in the investigation of serious crimes.

The articles reviewed for this discussion have been selected from those identified by the MedLine search. The authors have tried to objectively select those studies which best illustrate the points of discussion. However, by their nature, reviews cannot include every article of merit on the subject. Those readers interested in the full list of articles returned by the search are directed to the website of the British Assoiation of Forensic Odontology (BAFO, www.bafo.org.uk) and to the list of bitemark references (www.bafo.org.uk/bitemarkref.html). Each article is fully referenced with a brief synopsis.

The inherent difficulties of bitemark research, coupled with the professional status of forensic dental practitioners, means that advances to fully objectify bitemark analysis may be slow. There is a perceived acceptability in the level of scientific support for bitemark conclusions. Yet, with the new level of judicial interest in the validity of forensic evidence, it is likely that odontologists will have to revisit many of these issues.

Acknowledgement

Mr Pretty has been supported by the Forensic Science Society by the means of a research grant.

References

1. Pretty IA, Sweet D. Anatomical location of bitemarks and associated findings in 101 cases from the United States. Journal of Forensic Sciences 2000; 45(4): 812–4.
2. Pretty IA and Sweet D. Teeth in the determination of human identity. British Dental Journal 2001;190 (7): 359–366.
3. Rothwell BR. Bite marks in forensic dentistry: a review of legal, scientific issues. Journal of the American Dental Association 1995; 126(2): 223–32.
4. McCabe J. Applied dental materials. 7th ed. London: Blackwell Scientific; 1995.
5. Atsu SS, Gokdemir K, Kedici PS, Ikyaz YY. Bitemarks in forensic odontology. Journal of Forensic Odontostomatology 1998; 16(2): 30–4.
6. Stoddart TJ. Bite marks in perishable substances. A method of producing accurate permanent models. British Dental Journal 1973; 135(6): 285–7.
7. Marshall W. Bitemarks in perishable substances – forensic aspects. Criminology 1974; 9(32): 21–34.
8. Simon A, Jordan H, Pforte K. Successful indentification of a bite mark in a sandwich. International Journal of Forensic Dentistry 1974; 2(3): 17–21.
9. Kerr NW. Apple bitemark indentification of a suspect. International Journal of Forensic Dentistry 1977; 2: 17–22.
10. Corbett ME, Spence D. A forensic investigation of teeth marks in soap. British Dental Journal 1984; 157(8): 270–1.
11. Sweet D and Pretty IA. Teeth as weapons of violence. British Dental Journal 2001; In Press.
12. Sopher IM. Forensic dentistry. Springfield, IL: Charles C. Thomas; 1976.
13. Breathnach AS. The Herman Beerman lecture: embryology of human skin, a review of ultrastructural studies. Journal of Investigative Dermatology 1971; 57(3): 133–43.
14. DeVore DT. Bite marks for identification? A preliminary report. Medicine, Science and the Law 1971; 11(3): 144–5.
15. Barbenel JC, Evans JH. Bite marks in skin—mechanical factors. Journal of the Forensic Science Society 1974; 14(3): 235–8.
16. Rawson RD, Brooks S. Classification of human breast morphology important to bite mark investigation. American Journal of Forensic Medicine and Pathology 1984; 5(1): 19–24.
17. Krauss TC. Photographic techniques of concern in metric bite mark analysis. Journal of Forensic Sciences 1984; 29(2): 633–8.
18. Hyzer WG, Krauss TC. The bitemark standard reference scale – ABFO No. 2. Journal of Forensic Sciences 1988; 33(2): 498–506.
19. Hale A. The admissibility of bitemark evidence. Southern Californian Law Review 1978; 51(3): 309–34.
20. MacFarlane TW, MacDonald DG, Sutherland DA. Statistical problems in dental identification. Journal of the Forensic Science Society 1974; 14(3): 247–52.
21. *State* v. *Garrison*, 120 Ariz. 255, 585 P.2d 563, 1978.
22. Sognnaes RF, Rawson RD, Gratt BM, Nguyen NB. Computer comparison of bitemark patterns in identical twins. Journal of the American Dental Association 1982; 105(3): 449–51.
23. Rawson RD, Ommen RK, Kinard G, Johnson J, Yfantis A. Statistical evidence for the individuality of the human dentition. Journal of Forensic Sciences 1984; 29(1): 245–53.
24. Sweet D, Bowers CM. Accuracy of bite mark overlays: a comparison of five common methods to produce exemplars from a suspect's dentition. Journal of Forensic Sciences 1998; 43(2): 362–7.
25. Solheim T, Leidal TI. Scanning electron microscopy in the investigation of bite marks in foodstuffs. Forensic Science 1975; 6(3): 205–15.
26. Rao VJ, Souviron RR. Dusting and lifting the bite print: a new technique. Journal of Forensic Sciences 1984; 29(1): 326–30.
27. Elliot TR, Rodgers AH, Haverkamp JR, Groothuis D. Analytical pyrolysis of streptococci on human skin as an aid to identification in bitemark investigation. Journal of Forensic Odontostomatology 1984; 4(2): 12–7.
28. Nambiar P, Bridges TE, Brown KA. Quantitative forensic evaluation of bite marks with the aid of a shape analysis computer program: Part 1; The development of "SCIP" and the similarity index. Journal of Forensic Odontostomatology 1995; 13(2): 18–25.
29. Nambiar P, Bridges TE, Brown KA. Quantitative forensic evaluation of bite marks with the aid of a shape analysis computer program: Part 2; "SCIP" and bite marks in skin and foodstuffs. Journal of Forensic Odontostomatology 1995; 13(2): 26–32.
30. Guidelines for bite mark analysis. American Board of Forensic Odontology, Inc. Journal of the American Dental Association 1986; 112(3): 383–6.
31. Vale GL, Rawson RD, Sperber ND, Herschaft EE. Discussion of "Reliability of the scoring system of the American Board of Forensic Odontology for Human Bite Marks" [letter]. Journal of Forensic Sciences 1988; 33(1): 20.
32. Naru AS, Dykes E. Digital image cross–correlation technique for bite mark investigations. Science & Justice 1997; 37(4): 251–8.
33. Zarkowski P. Bite mark evidence: its worth in the eyes of the expert. Journal of Law and Ethics in Dentistry 1988; 1(1): 47–57.
34. Sweet D, Lorente JA, Valenzuela A, Lorente M, Villanueva E. PCR–based DNA typing of saliva stains recovered from human skin. Journal of Forensic Sciences 1997; 42(3): 447–51.
35. Sweet D, Shutler GG. Analysis of salivary DNA evidence from a bite mark on a body submerged in water. Journal of Forensic Sciences 1999; 44(5): 1069–72.